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P.O. Box 245
Berkeley
California 94701

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Fuel Models to Predict Fire Behavior in Untreated Conifer Slash

Lucy A. Salazar Collin D. Bevins

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Fire behavior in untreated slash of nine conifer species was simulated for 10 successive years after logging. Two aging factors that affect fire behavior—fuel bed compaction and foliage retention—were modeled by least squares regression techniques. On the basis of spread rate and flame length for a set of weather observations, standard Northern Forest Fire Laboratory fuel models were chosen to predict fire behavior for aging slash of each species at three initial fuel loadings. Differences in the standard fuel model sequences best representing the aging process among species were most influenced by foliage surface-area-to-volume ratio, and such differences increased as initial fuel load increased. The modeled fire behavior potential decreased over time for almost all species studied. The modeling techniques are applicable to long-term fire management planning models.

Retrieval Terms: fuel models, slash, fire behavior, fire hazard

Current fuel management policy in the National Forest System is to meet both fire management and resource objectives in a cost-efficient manner.[1] One function of the Fire Economics Evaluation System (FEES) being developed at the Pacific Southwest Forest and Range Experiment Station is to assess fuel treatment options in terms of their cost and effect on resources.[2] The system uses data on periodic changes in simulated fire behavior as a basis for evaluating alternative fuel treatment options for long-term planning.

A fuel management option in cutover stands is nontreatment. To simulate fire behavior in untreated slash fuel beds, the changes in fuel beds over time must be quantified. Fuel loads and depth in natural fuels[3] and activity fuels that had been logged a year or two earlier[4] have been measured or predicted in other studies. Fuel arrays or arrangements varied over time and location in terms of quantity, compaction, decomposition, and flammability. These four factors affect stand fire hazard or fire-spread potential by affecting difficulty of fire suppression and ease of ignition.

This note reports a study of predicting fire behavior in untreated fuels of nine conifer species at three initial fuel loadings by using regression techniques to model two aging processes in slash—fuel bed compaction and foliage retention. Live fuels were omitted from the study because of the variability in vegetative successional patterns between sites.

Simulated fire behavior potential in untreated slash decreased over time for almost all nine species studied, in the light and medium fuel-loading categories. In the heavy fuel-loading category, even after 10 years, many species still showed potential for severe fire behavior. The sequence of recommended fuel models best representing the slash aging process differed among species and initial fuel loads. Stylized or standardized fuel models[5,6] can be used to estimate fire behavior in untreated slash fuels of the nine species studied up to 10 years after cutting, for the purpose of long-range fire management planning.

Aging of Slash Fuels

Over time, all fuels are affected by aging processes. These processes include (a) fuel compaction, (b) foliage retention, and (c) particle decomposition. Compaction of the fuel bed results from loss of the elevated components of the fuel array due to needle drop and checking and breakup of the finer woody particles. The shifting of finer fuels to the lower portions of the fuel array not only decreases fuel bed depth, but significantly alters the fuel bed vertical profile by increasing fuel bulk density in the lower bed. These processes generally reduce fire behavior potential in slash fuels. The weight of winter snow and the slash itself may also contribute to bed compaction over time.

The second aging process affecting slash fuel conditions is the loss of foliage the first few years after cutting. The high flammability of fresh and red (cured) slash is primarily due to the finer fuels, such as foliage and small twigs, that are supported throughout the fuel bed profile. Most spe-

cies lose their foliage during the first 1 to 5 years after cutting. Furthermore, the rate of needle retention apparently varies between species. Foliage loss is perhaps the most significant event affecting slash flammability during this time span and may significantly reduce potential fire behavior.

The third aging process is decomposition of woody particles. While decay of woody particles is ultimately responsible for the reduction of slash fuels to natural conditions, it is a slow process that may not be appreciable during the first 10 years after cutting. This is particularly the case in the Intermountain West where long, cold winters and hot, dry summers create an unfavorable environment for decay fungi.

Stylized Fuel Models

Forest fuel beds are commonly represented by stylized fuel models used as inputs to Rothermel's fire spread model,[5,6] the most comprehensive and widely-used mathematical wildland fire spread model to date. It has been shown to predict rate-of-spread with acceptable accuracy in both experimental and on-going fire situations.[7] Methods have been devised for site-specific verification and adjustment of fire behavior predictions[8] but this flexibility is not feasible within the context of a long-term planning system. We assumed that the general level of precision displayed by Rothermel's fire spread model was adequate for the resolution of this modeling exercise.

The stylized fuel models most widely used and accepted for fire behavior simulation are the 13 Northern Forest Fire Laboratory (NFFL) fire behavior models.[5,6] They differ in their fuel particle size class loadings and surface-area-to-volume ratios, fuel bed depths, moisture contents of extinction, and wind reduction factors.

The stylized fuel models, by necessity, represent discrete points along the distribution of actual fuel populations. Fuel loadings and bed depths, for example, are known to vary widely due to natural differences in species composition, stocking levels, diameter distributions, site characteristics, and stand history. Slash fuel loads and depths are further affected by cutting method, removal technique, fuel treatment method and intensity, and years since cutting. The wide variability in slash fuel beds and fire behavior is represented by three of the NFFL stylized fuel models: model 11 for light, model 12 for medium, and model 13 for heavy slash loading conditions. Selection of an appropriate NFFL slash model to represent potential fire behavior in recently cutover stands was described by Rothermel.[6]

This note recommends standardized fuel models to best represent expected fire behavior in slash fuels of nine conifer species, at three initial fuel loads, and up to 10 years after cutting, for the purposes of long-range fire management planning. Live fuels were omitted from the analysis because of the variability in vegetative successional patterns between sites.

Table 1—*Customized fuel model parameters for untreated slash of nine conifer species, by fuel particle size*

Slash species	Fraction of total fuel loading[1]				Surface-area-to-volume ratio (1/ft)[2]			
	Needles	1-hr	10-hr	100-hr	Needles	1-hr	10-hr	100-hr
Ponderosa pine	0.236	0.007	0.374	0.383	1,756	259.4	85.3	28.6
Western white pine	.253	.166	.251	.330	2,758	270.9	97.5	30.3
Lodgepole pine	.153	.114	.379	.354	1,972	304.8	91.0	25.7
Western larch	.117	.191	.403	.289	5,608	393.3	91.0	31.7
Douglas-fir	.276	.115	.216	.393	2,106	435.4	91.0	28.6
Grand fir	.374	.154	.251	.221	2,222	435.4	91.0	28.6
Engelmann spruce	.296	.148	.173	.383	1,652	435.4	91.0	31.7
Western hemlock	.230	.145	.192	.433	3,042	580.6	78.7	26.3
Western red cedar	.358	.074	.216	.352	1,000	435.4	85.3	31.7

[1]Published data (see note 12) or derived from published data (see note 13).
[2]Published data (see note 14). 1 ft = 0.3048 m.

METHODS

Previously published data were used to develop regression equations to portray slash foliage retention and fuel bed compaction for nine common species in northern Idaho,[9] northern California,[10] and Alberta[11] (*table 1*): ponderosa pine (*Pinus ponderosa* Laws.), western white pine (*P. monticola* Dougl.), lodgepole pine (*P. contorta* Dougl.), western larch (*Larix occidentalis* Nutt.), Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco), grand fir (*Abies grandis* [Dougl.] Lindl.), Engelmann spruce (*Picea engelmannii* Parry), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), and western red cedar (*Thuja plicata* Donn.). Least squares regression equations for slash compaction were developed for each species in the form:

$$f_{st} = a_s C_s^t \qquad (1)$$

in which

f_{st} = fraction [0,1] of the fuel bed's original depth at time t (t>0) for species s
t = time (number of winters) since cutting
a_s = a species-specific constant
C_s = compaction ratio of species s

Fuel beds that compact the quickest have the lowest C_s values.

The same and additional data[12] were used to derive annual needle retention equations in the form:

$$p_{st} = R_s^t \qquad (2)$$

in which

p_{st} = proportion [0,1] of the needle load remaining on the slash twigs at time t for species s
R_s = needle retention rate of species s
t = time (number of winters) since cutting

Species that best retain their foliage have high R_s values. We did not attempt to derive needle retention rates using least squares regression techniques because observations in the literature were mostly qualitative. At best, the percentage of needles remaining suspended in the fuel array had been ocularly estimated from time to time.

Species-specific or customized slash fuel models were developed for each of the nine conifer species at three fuel loads and initial bed depths that corresponded to those used in the NFFL stylized models for light, medium, and heavy slash loading. Fuel loadings by individual fuel particle size class within each customized model were redistributed for the nine species us

Table 2—*Fuel bed compaction and needle retention ratios for customized fuel models for untreated slash of nine conifer species*

Slash species	Sample size	Fuel bed compaction ratios				Needle retention ratios
		Equation parameters[1]		Regression statistics		
		a	C	r-square	F-ratio	
Ponderosa pine	20	0.845	0.935	0.86	115.0	0.7
Western white pine	9	1.087	.838	.75	20.7	.7
Lodgepole pine	19	1.032	.880	.54	20.0	.7
Western larch	9	.935	.870	.50	6.9	.5
Douglas-fir	9	.990	.995	[2].00	.1	.5
Grand fir	9	.932	.781	.96	156.7	.5
Engelmann spruce	19	1.127	.777	.77	57.2	.3
Western hemlock	9	1.012	1.017	.08	.6	.3
Western red cedar	9	.985	.951	.35	3.8	.7

[1]a = species-specific constant.
C = compaction ratio.
[2]r-square < 0.005.

ing loading fractions published earlier[12] or derived from published data[13] *(table 1)*. A separate fuel size class for needles was also introduced. Published surface-area-to-volume ratios for each species were used[14] *(table 1)*. All other fuel model parameters (including total initial fuel load, fuel bed depth, and wind reduction factors) were the same as those for the corresponding NFFL light, medium, or heavy slash fuel models.

The customized slash fuel models were then "aged" over 10 winters using equations (1) and (2) for each of the nine species. Due to the established structure of the fuel treatment module of FEES, it was necessary to convert each of the 297 customized inputs back into the NFFL fuel model that best represented its resultant fire behavior.

Fire behavior predictions for the 13 NFFL stylized fuel models and the 297 customized slash fuel models were obtained using a mathematical fire spread model[6] adapted by the National Fuel Appraisal Project.[15] Weather observations used in the model were taken at 1400 local standard time in Missoula, Montana, during April 1-October 31, 1955-74 (4276 observations).

The squared differences in daily fire spread rate and flame length predictions between each NFFL and customized slash fuel model pair were summed over all 4276 samples. The sum of the squared differences between each model pair was then divided by the sample size and its square root derived. The resulting value was the standard deviation of a customized slash fuel model's predicted fire behavior from that of an NFFL fuel model. The NFFL fuel model chosen as best representing each of the 297 different combinations of loading levels, species, and years since cutting was that with the smallest standard deviation. Because the customized inputs were species-specific, we assumed that the chosen "best" NFFL fuel model would, in turn, produce more realistic fire behavior predictions than the stylized light, medium, or heavy slash models. Because absolute differences in predicted fire behavior between fuel models are greatest under extreme fire weather conditions, this computational procedure tends to select NFFL fuel models that most closely resemble customized fuel model predictions under high and extreme conditions.

Table 3—*Predicted mean spread rates and flame lengths for Northern Forest Fire Laboratory (NFFL) fuel models, on the basis of 4276 weather observations at Missoula, Montana*[1]

NFFL fuel model and description	Spread rate	Flame length
	ft/min	*ft*
1. Short grass (1 ft)	58.7	3.6
2. Timber (grass and understory)	20.0	4.8
3. Tall grass (2.5 ft)	101.7	12.2
4. Chaparral (6 ft)	85.8	20.0
5. Shrubs (2 ft)	16.1	4.7
6. Dormant shrubs, hardwood slash	29.5	5.6
7. Southern rough	15.1	4.2
8. Closed timber litter	.9	.7
9. Hardwood litter	3.2	1.8
10. Timber (litter and understory)	3.0	3.1
11. Light logging slash	4.5	2.9
12. Medium logging slash	11.8	7.4
13. Heavy logging slash	15.2	9.9

[1]1 ft = 0.3048 m.

RESULTS AND DISCUSSION

Fuel Bed Compaction and Foliage Retention

Engelmann spruce and grand fir slash fuel beds were estimated to have low compaction ratios, which indicate that they compact faster than the other species examined *(table 2)*. Western white pine, western larch, and lodgepole pine had intermediate compaction rates. Douglas-fir and western red cedar compacted more slowly. Western hemlock slash depth after 5 years actually increased[9] due to curling of branches. This is reflected in its high compaction ratio. The age at which hemlock slash begins to compact was not found in the literature.

Englemann spruce and western hemlock, which were estimated to retain only 30 percent of their needles from one year to the next, had the lowest needle retention rates *(table 2)*. The three pines and western red cedar had the highest rates.

Fuel Model Predictions

Mean spread rates and flame lengths were also predicted for the 13 NFFL stylized fuel models on the basis of the 4276 weather observations *(table 3)*.

NFFL fuel models 11 (light slash), 10 (timber litter and understory), 9 (hardwood litter), and 8 (closed timber litter) best represented the aging sequence of light conifer slash from 0 to 10 winters after cutting *(table 4)*. Light slash from zero through two winters was best represented by model 11,

Table 4—*Northern Forest Fire Laboratory (NFFL) fuel models that best represent aging slash, and standard deviations (SD) of spread rate and flame length from customized fuel models, for light, medium, and heavy initial fuel loadings for nine conifer species*

Slash species and age (years)	NFFL fuel model[1] when slash loading is...			Spread rate (SD) when slash loading is...			Flame length (SD) when slash loading is...		
	Light	Medium	Heavy	Light	Medium	Heavy	Light	Medium	Heavy
Ponderosa pine									
0	11	13	13	2.61	3.89	10.45	0.47	1.56	1.49
1	11	12	12	0.57	1.41	2.75	0.55	1.65	0.43
2	9	12	12	0.80	3.69	1.16	0.36	2.47	1.09
3	9	11	12	0.67	3.89	2.70	0.31	1.76	1.54
4	9	11	12	0.68	3.44	3.36	0.34	1.86	1.44
5	9	11	12	0.67	3.47	3.50	0.45	2.29	1.00
6	9	12	12	0.66	5.06	3.36	0.70	1.54	0.55
7	11	12	12	1.58	4.78	3.20	0.23	0.72	1.20
8	11	12	12	1.55	4.47	3.16	0.44	0.61	2.39
9	10	12	12	1.37	4.63	3.45	1.00	1.48	3.57
10	10	12	12	1.29	5.06	3.93	1.20	2.24	4.64
Western white pine									
0	12	6	6	2.98	4.14	15.36	4.23	2.66	5.51
1	11	2	6	3.64	5.33	4.29	0.54	1.59	2.65
2	11	7	2	0.88	4.97	6.21	1.17	1.09	1.24
3	9	11	12	0.92	5.18	2.37	0.56	0.53	3.33
4	9	11	11	1.23	1.93	3.76	0.75	0.47	0.51
5	8	11	11	1.07	0.81	1.08	0.31	0.77	0.52
6	8	9	9	0.64	0.61	0.78	0.26	0.22	0.31
7	8	9	9	0.31	1.13	1.01	0.22	0.22	0.19
8	8	8	8	0.24	0.84	0.72	0.17	0.70	0.55
9	8	8	8	0.42	0.23	0.16	0.19	0.42	0.21
10	8	8	8	0.58	0.32	0.53	0.23	0.19	0.19
Lodgepole pine									
0	11	12	13	0.59	2.15	3.19	0.43	1.20	1.61
1	9	12	12	1.18	2.17	1.85	0.41	2.16	0.61
2	9	11	12	0.66	4.17	2.20	0.30	1.80	1.38
3	9	11	12	0.82	2.60	4.41	0.29	1.60	1.76
4	9	11	11	1.04	1.52	2.94	0.30	1.59	2.70
5	9	11	11	1.32	0.80	1.67	0.33	1.68	2.61
6	9	11	11	1.55	0.77	0.92	0.38	1.73	2.55
7	9	10	11	1.85	1.28	1.19	0.40	1.56	2.35
8	8	10	10	0.66	0.73	0.75	1.30	1.35	1.71
9	8	10	10	0.41	0.86	0.85	1.23	1.07	1.22
10	8	10	10	0.23	1.35	1.45	1.08	0.68	0.63
Western larch									
0	2	1	3	8.76	31.03	54.28	2.65	2.63	4.30
1	11	6	1	8.32	15.18	28.58	1.40	1.69	2.24
2	11	2	6	4.07	8.07	9.35	1.39	1.18	0.82
3	11	7	2	1.28	5.16	5.69	1.19	1.08	0.85
4	9	12	12	1.01	3.56	1.59	0.33	3.08	2.32
5	9	11	11	0.87	1.56	2.41	0.44	1.71	2.30
6	9	11	11	1.59	1.12	1.02	0.48	1.76	2.21
7	8	10	10	0.56	0.69	0.67	1.34	1.32	1.57
8	8	10	10	0.23	1.24	1.36	1.20	0.89	0.81
9	8	10	10	0.27	1.89	2.03	0.93	0.39	0.40
10	8	8	8	0.45	0.18	0.21	0.58	1.59	1.31
Douglas-fir									
0	11	2	6	4.37	5.13	2.01	0.57	4.03	6.09
1	11	12	13	0.83	3.11	4.90	0.61	1.56	1.89
2	9	12	12	1.19	1.94	2.73	0.31	2.47	0.68
3	9	12	12	1.05	2.30	1.83	0.42	1.89	0.60
4	11	12	13	0.85	1.87	1.87	0.35	0.60	0.29
5	11	12	13	1.03	2.36	2.44	0.15	0.62	1.96
6	11	12	13	1.61	3.65	3.78	0.20	0.91	2.82
7	10	12	12	0.90	5.09	2.55	0.76	0.72	5.18
8	9	12	12	1.05	6.19	3.20	0.70	0.63	4.74
9	9	11	12	1.28	2.60	3.83	0.57	4.14	4.35
10	9	11	12	1.48	2.21	4.22	0.48	3.90	4.11

Table 4—*Northern Forest Fire Laboratory (NFFL) fuel models that best represent aging slash, and standard deviations (SD) of spread rate and flame length from customized fuel models, for light, medium, and heavy initial fuel loadings for nine conifer species (continued)*

Slash species and age (years)	NFFL fuel model[1] when slash loading is...			Spread rate (SD) when slash loading is...			Flame length (SD) when slash loading is...		
	Light	Medium	Heavy	Light	Medium	Heavy	Light	Medium	Heavy
Grand fir									
0	12	6	6	1.97	2.33	15.11	3.00	5.71	9.57
1	11	12	13	0.82	2.84	4.13	0.60	1.75	2.50
2	9	11	11	0.93	2.69	4.84	0.45	0.72	1.64
3	8	11	11	0.96	0.85	0.70	0.50	0.34	0.64
4	8	9	10	0.48	0.60	0.90	0.50	0.80	0.43
5	8	9	10	0.18	1.65	1.32	0.44	0.52	0.73
6	8	8	8	0.39	0.31	0.18	0.30	1.16	0.96
7	8	8	8	0.60	0.36	0.48	0.18	0.53	0.31
8	8	8	8	0.80	0.70	0.82	0.31	0.14	0.33
9	8	8	8	0.91	0.90	0.95	0.71	0.71	0.72
10	8	8	8	0.95	0.96	0.97	0.72	0.72	0.72
Engelmann spruce									
0	11	13	13	2.75	3.84	10.32	0.87	0.67	2.85
1	9	12	12	0.65	4.11	1.11	0.39	2.06	0.41
2	9	11	12	1.03	1.87	5.21	0.43	2.58	0.57
3	9	11	11	1.67	0.94	1.63	0.54	2.94	4.98
4	8	10	10	0.51	0.73	1.17	1.32	2.07	3.57
5	8	10	10	0.20	1.19	0.98	1.02	1.05	1.81
6	8	10	10	0.35	1.97	2.02	0.67	0.42	0.40
7	8	8	8	0.60	0.29	0.38	0.28	0.99	0.79
8	8	8	8	0.77	0.67	0.77	0.22	0.18	0.19
9	8	8	8	0.88	0.87	0.93	0.50	0.44	0.72
10	8	8	8	0.95	0.95	0.97	0.72	0.72	0.72
Western hemlock									
0	11	6	6	7.39	5.12	16.69	0.29	1.92	4.52
1	11	7	2	1.13	4.94	5.21	1.12	1.18	1.93
2	11	12	13	0.35	1.62	2.91	0.61	1.41	1.46
3	11	12	13	0.30	1.11	2.18	0.16	0.85	2.11
4	11	12	13	0.81	1.76	2.13	0.34	1.62	3.76
5	11	12	13	1.25	2.70	2.73	0.27	1.57	4.00
6	11	12	13	1.39	2.98	2.99	0.24	1.52	4.05
7	11	12	13	1.45	3.01	2.97	0.22	1.51	4.12
8	11	12	13	1.40	2.97	2.91	0.23	1.52	4.19
9	11	12	13	1.35	2.82	2.81	0.23	1.56	4.28
10	11	12	13	1.30	2.70	2.74	0.23	1.59	4.37
Western red cedar									
0	12	13	13	5.10	5.87	12.59	1.55	5.44	11.06
1	11	13	13	2.03	1.62	6.88	1.96	2.68	7.49
2	11	13	13	0.71	2.69	2.78	1.14	0.87	4.89
3	11	12	13	0.56	1.43	1.73	0.58	1.75	3.04
4	11	12	13	1.21	3.15	3.70	0.23	0.85	1.87
5	10	12	12	1.06	4.48	1.97	0.63	0.43	3.65
6	10	12	12	0.90	5.46	2.96	0.70	0.43	3.29
7	10	12	12	0.90	6.35	3.93	0.76	0.58	3.08
8	10	11	12	1.00	2.21	4.79	0.83	4.02	2.93
9	9	11	12	1.37	1.64	5.62	0.66	3.81	2.75
10	9	11	12	1.60	1.26	6.37	0.58	3.59	2.53

[1]See *table 3* for NFFL fuel models and descriptions.

from three through four winters by model 9, and thereafter by model 8. Species appeared to differ; grand fir slash reverted to model 8 after three winters, while western hemlock remained in model 11 for the entire 10-year period.

Medium logging slash from 0 through 2 years was best modeled by fuel model 6 (dormant shrubs, hardwood slash), model 2 (timber and grass), or model 12 (medium logging slash), depending on the conifer species *(table 4)*. Small-needled species with needle surface-area-to-volume ratios over 2000 ft^{-1} were best predicted by models 2 and 6, and all others by model 12 (*table 1*). Model 11 best predicted fire behavior during years 3-6, followed by model 10, and finally by model 8.

Heavy logging slash during the first year or two after cutting was best represented by fuel model 6 or 2 for small-needled species, and by model 13 (heavy slash) for large-needled species *(table 4)*. As the heavy fuel beds aged, they were also best represented by models 12, 11, 10, and 8, sequentially.

Species differences in the aging sequence appeared to be most affected by foliage surface-area-to-volume ratio. As initial fuel loadings increased, so did species differences. Western larch needles, for example, have a high surface-area-to-volume ratio *(table 1)*. As a result, fire behavior in this type during the first few years after cutting was severe and was best represented by models representing grass and shrub fuels.

The modeling techniques used in this analysis are primarily applicable to long-term planning models that require simulations of fuel treatment programs over several years.[2] The results could also provide information useful for setting priorities of areas to treat based on their potential fire behavior and resulting risk over time. Further analysis is necessary to determine whether simulated differences in fire behavior potential among species and initial fuel loadings would be substantial in an economic efficiency evaluation.

NOTES

[1]U.S. Department of Agriculture, Forest Service. *FSM 5150—Fuel management*, Interim Directive 16. Washington, DC; 1983. 6 p.

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The Authors:

LUCY A. SALAZAR is a research forester assigned to the Station's Fire Management Planning and Economics Research Unit, headquartered at the Forest Fire Laboratory, Riverside, California. She earned a bachelor's degree (1976) in mathematics from the University of California, Irvine, and a master's degree in natural resources with an emphasis in forestry, at Humboldt State University, Arcata (1980). She joined the Station staff in 1980. **COLLIN D. BEVINS** is a research forester with Systems for Environmental Management in Missoula, Montana. He received a bachelor of arts degree (1974) from Carleton College, Minnesota, in biology and a master of science degree (1975) in forestry from the University of Washington, Seattle.

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